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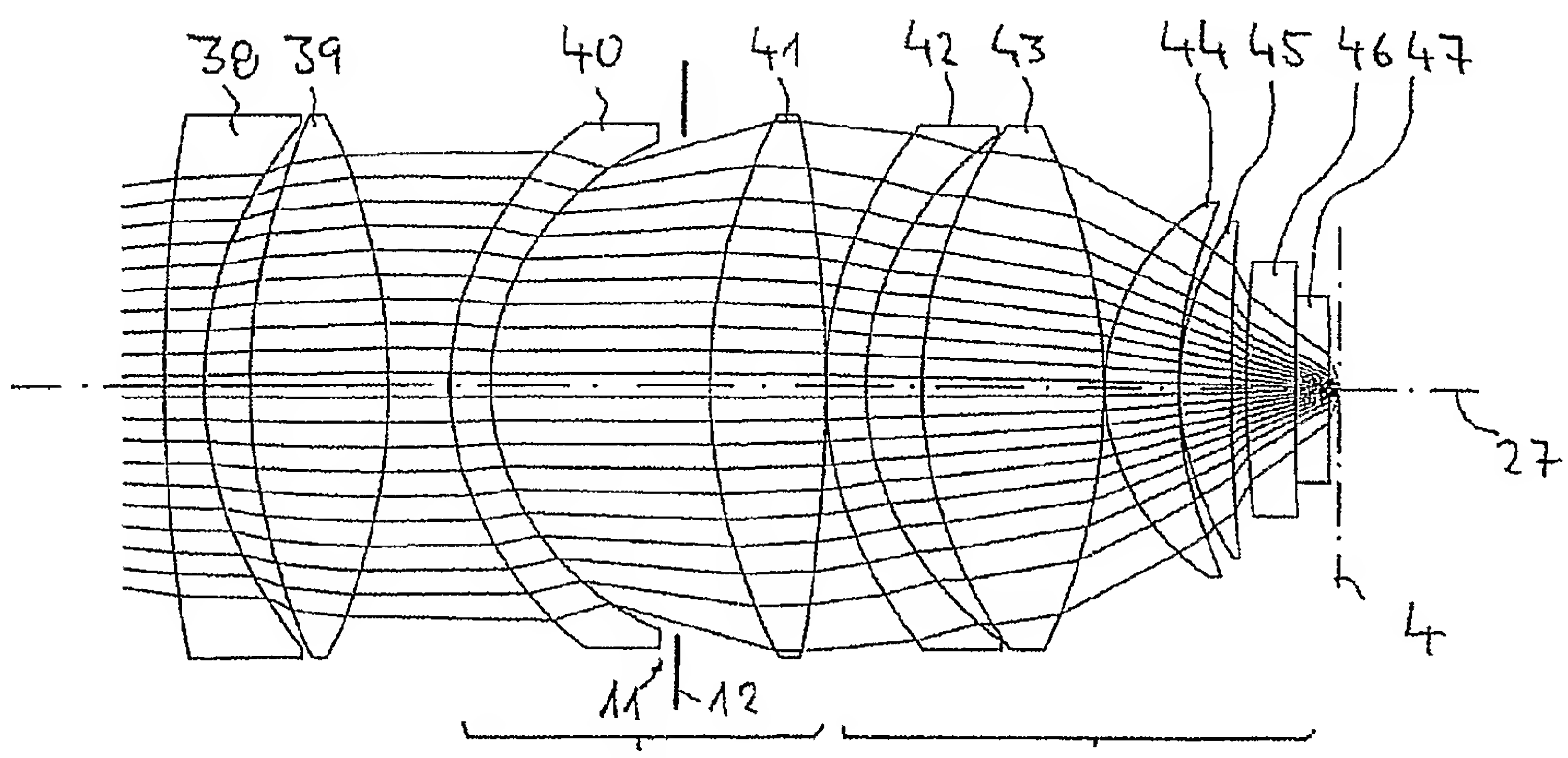

(57) Abstract: A projection objective for projecting a pattern of a mask arranged in an object plane of the projection objective into an image plane of the projection objective has a pupil surface (11) near the image plane, a radiance transformation group (100) that is arranged at a distance upstream of the image plane (4); and an aperture-generating group (200) arranged downstream of the radiance transformation group. The radiance transformation group is designed to transform an input radiance distribution with a uniform angular radiance that is substantially independent of beam height into an output radiance distribution with a nonuniform angular radiance that is dependent on beam height, wherein the angular radiance decreases with increasing beam height, at least in a region near a maximum beam height. The output radiance distribution is adapted to beam guidance properties of the aperture-generating group in such a way that the sine condition is substantially fulfilled in the image plane for all beams of the input light distribution.

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PROJECTION OBJECTIVE FOR MICROLITHOGRAPHY

[0001] The invention relates to a projection objective for projecting a pattern arranged in the object plane of the projection objective into the image plane of the projection objective.

[0002] Such projection objectives are used in microlithography projection exposure machines for producing semiconductor components and other finely structured components. They serve the purpose of projecting patterns of photomasks or lined plates, generally referred to below as masks or reticles, onto an article coated with a photosensitive layer of very high resolution on a demagnifying scale.

[0003] In this case, the production of ever finer structures necessitates, on the one hand, enlarging the image-side numerical aperture NA of the projection objective and, on the other hand, using ever shorter wavelengths, preferably ultraviolet light with wavelengths of less than approximately 260 nm, for example 248 nm, 193 nm or 157 nm.

[0004] For wavelengths of down to 193 nm, it is possible to operate with purely refractive (dioptric) projection systems which can be produced under effective control because of their rotation of symmetry about the optical axis. In order to achieve very small resolutions, however, it is necessary here to operate with very large numerical apertures NA of more than 0.8 or 0.9. These can be implemented only with difficulty for dry systems with a sufficiently large, finite working distance (distance between the exit surface of the objective and the image plane). Again, refractive immersion systems have already been proposed that permit values of NA > 1 by the use of an immersion

fluid of high refractive index between the objective exit and image plane.

[0005] However, for the abovementioned short wavelengths, it is becoming ever more difficult to provide purely refractive systems with adequate correction of chromatic aberrations, since the Abbe constants of suitable, transparent materials are relatively close to one another. Consequently, catadioptric systems are predominantly used for very high-resolution projection objectives, refracting and reflecting components, that is to say lenses and mirrors, in particular, being combined in the case of such systems.

[0006] When use is made of imaging reflecting surfaces, it is necessary to employ beam deflecting devices if the aim is to achieve imaging that is free from obscuration and vigneting. Both systems with geometric beam splitting by means of one or more fully reflecting folding mirrors (deflecting mirrors), and systems with physical beam splitting are known. Moreover, further plane mirrors can be used for folding the beam path. These are generally used in order to fulfill specific installation space requirements, or to align object and image planes parallel to one another. These folding mirrors are not mandatory in optical terms.

[0007] The use of a physical beam splitter, for example in the form of a beam splitter cube (BSC) with a polarization-selective beam splitter surface, permits projection objectives to be implemented with an objective field centered around the optical axis (on-axis systems). A disadvantage of such systems is that suitable transparent materials for the production of a beam splitter cube are available only conditionally in the large volumes required. Moreover, the production of the polarization-selectively active beam splitter layers can pose substantial difficulties. An incomplete

polarization-selective effect can lead to the production of leakage transmission dependent on the angle of incidence, and thus to intensity inhomogeneities in imaging.

[0008] The disadvantages of systems with polarization-selective beam splitters can largely be avoided in systems with geometric beam splitting, that is to say when use is made of fully reflecting folding mirrors in the beam deflecting device. Such a folding mirror permits the optical path leading to a concave mirror to be separated in space from the optical path leading away from the concave mirror. Many problems that can arise from the use of polarized light are eliminated.

[0009] Various folding geometries are possible for projection objectives with geometric beam splitting, there being specific advantages and disadvantages depending on the course of the light path between the object field and image field.

[0010] Patent US 6,195,213 B1 shows various embodiments of projection objectives with geometric beam splitting for projecting a pattern of a mask arranged in an object plane of the projection objective into an image plane of the projection objective with the production of a single, real intermediate image. The projection objectives, which achieve image-side numerical apertures of up to NA = 0.75, have a catadioptric first objective part that is arranged between the object plane and the image plane and has a concave mirror as well as a beam deflecting device, and a dioptric second objective part, which is arranged between the first objective part and the object plane. The beam deflecting device has a first folding mirror, which is arranged in the beam path between the concave mirror and the image plane. In these systems, the folding mirror is arranged such that light coming from the object plane firstly falls onto the concave mirror of

the first objective part before it is reflected by the latter to the first folding mirror. It is deflected by 90° by the latter and reflected to a second folding mirror, which deflects the radiation coming from the first folding mirror by 90° again in the direction of the image plane. This radiation guidance leads to an h-shaped design of the system, for which reason this folding geometry is also denoted as h-folding.

[0011] A number of lenses serving the purpose of optical correction are accommodated in the installation space between the object plane and first folding mirror. The region between the folding mirrors is free from lenses, the aim thereby being to facilitate a compact design. Consequently, all the lenses and the concave mirror are arranged in objective parts that can be vertically aligned, the aim being thereby to achieve a design that is stable against influences of gravity. The elements of the first objective part that are used to produce the intermediate image are designed such that the intermediate image is situated in the vicinity of the first folding mirror. The optical components following the intermediate image serve the purpose of refocusing the intermediate image onto the image plane, which can be aligned parallel to the object plane owing to the dual folding by the folding mirrors.

[0012] Middle-aperture projection objectives with h-folding geometry and image-side numerical apertures of NA = 0.6 are shown in Patent US 6,157,498. With this system, the installation space between the object plane and first folding mirror is free from lenses, while a multiplicity of lenses with large diameters are accommodated in the horizontally aligned region between the first and second folding mirrors.

[0013] Other projection objectives with h-folding, in the case of which lenses are arranged in the installation space between the object plane and first

folding mirror, are described in Patent US 5,969,882 (corresponding to EP-A-0 869 383). In embodiments for which the first and second folding mirrors are configured as reflecting surfaces of a deflecting prism, the region between the folding mirrors is free from refractive power.

[0014] EP-A-0 889 434 (corresponding to US Serial No 09/364382) shows projection objectives with a beam deflecting device designed as a reflecting prism. The reflecting prism forms a first folding mirror for deflecting the radiation coming from the object plane to the concave mirror, and a second folding mirror for deflecting the radiation reflected by the concave mirror to the second objective part, which includes only refractive elements. The catadioptric first objective part produces a real intermediate image that is situated in a freely accessible fashion at a distance downstream of the second reflecting surface. The concave mirror is fitted here in a side arm - projecting in the installed state in a fashion transverse to the vertical direction - of the projection objective, which is also denoted as "horizontal arm (HOA)". Because of the singly shaped geometry of the beam path, such a folding geometry is denoted as "single folding". Other projection objectives with single folding are described, for example, in DE 101 27 227 (corresponding to US patent application US 2003/021040) or international patent application WO 03/050587.

[0015] Systems with a geometric beam splitter have the disadvantage in principle that the object field is arranged eccentrically in relation to the optical axis (off-axis system). This places increased demands on the correction of aberrations, since by comparison with on-axis systems in conjunction with the same object field size, a larger useful field diameter must be adequately corrected in the case of such an imaging system. This

larger field region including the object field is also denoted below as "superfield".

[0016] It is an object of the invention to provide a projection objective that permits a high imaging quality in conjunction with a finite working distance even in the case of very high numerical apertures. In particular, a compact, catadioptric projection objective with geometric beam splitting and very high imaging quality is to be provided.

[0017] As a way of achieving this object, in accordance with one formulation of the invention the invention provides a projection objective for projecting a pattern of a mask arranged in an object plane of the projection objective into an image plane of the projection objective. The projection objective has:

a pupil surface near the image plane;

a radiance transformation group that is arranged at a distance upstream of the image plane; and

an aperture-generating group arranged downstream of the radiance transformation group;

wherein the radiance transformation group is designed to transform an input radiance distribution with a uniform angular radiance that is substantially independent of beam height into an output radiance distribution with a nonuniform angular radiance that is dependent on beam height, wherein the angular radiance decreases with increasing beam height, at least in a region near a maximum beam height, and

the output radiance distribution is adapted to beam guidance properties of the aperture-generating group in such a way that the sine condition is substantially fulfilled in the image plane for all beams of the input light distribution.

[0018] The invention takes account of the circumstance that in addition to the customary aberration correction the correction of the sine condition plays an important

role in the correction of high-aperture projection systems for microlithography which have a finite working distance in air (or in another gas). The correction of the sine condition becomes increasingly difficult with the size of the working distance, and requires special correcting means that are provided by the invention. It is required so that the imaging is performed with the same magnification ratio for different zones of the system cross section, it thereby being possible to avoid instances of unsharpness.

[0019] The following explanation serves the purpose of better comprehension of the invention. In conventional lens sectional illustrations, the rays are normally equidistantly arrayed in terms of the direction cosine in the object space, that is to say in the region of the object plane. This means that the direction cosines of two neighboring rays differ in each case by a constant. This condition corresponds to a uniform angular radiance, i.e. to a uniform radiance in angle-space (uniform density of rays in angle-space). Here, the direction cosine of a ray is understood as the sine of the angle between the ray and the optical axis. In the case of low numerical apertures, such as are typically present at the object, the ray angles are small, and therefore the absolute values of the ray angles themselves are quasi-equidistantly arrayed, since here the sine of an angle corresponds substantially to the angle itself. For high apertures, however, the geometric ray angles of the rays going to the edge of the pupil (edge rays) become large. In these cases, the geometric ray angles seem to be more coarsely arrayed toward the edge of the pupil than in the middle of the pupil. This situation corresponds to a non-uniform density of rays in angle space, i.e. to a non-uniform angular radiance. This effect is larger the larger the geometric ray angles, and the larger the distance from the next optical surface (propagation phenomenon).

[0020] Because of the corrected sine condition, the beam penetration points are then by far non-equidistant in the wafer space, particularly on the last, normally substantially flat optical surface of the projection objective immediately upstream of the image plane. This is correlated with the fact that the distance of two rays from the edge of the pupil appears stretched by comparison with the middle of the pupil. This effect is enhanced with increasing working distance and increasing aperture.

[0021] A corrected sine condition in the wafer space (image space) corresponds in this case to a uniform angular radiance at the image plane. This is ensured by means of projection objectives according to the invention.

[0022] In some embodiments, the radiance transformation group has a spherically overcorrecting first optical group and a downstream spherically undercorrecting second optical group, the first optical group preferably being arranged upstream of a pupil surface near the image of the projection objective, and the second optical group being arranged downstream of this pupil surface. In this case, the radiance transformation group is thus arranged as a whole in the region of the pupil surface and encloses the latter. It is thereby possible for a spherical aberration to be introduced at a suitable distance upstream of the image plane. An offset of the correction of the sine condition in the region of the pupil surface is set by propagation of the spherical aberration. However, in this case the aperture space, that is to say the region of the pupil surface itself, is by far not corrected for sine. The spherical aberration firstly introduced can be ameliorated so far by the spherically undercorrecting second optical group that a good state of correction is set up for the spherical aberration after passage through the aperture-generating group. At

the same time, a uniform angular radiance is produced in the image space, and this corresponds to a correction of the sine condition.

[0023] The spherical overcorrection is preferably provided by a hollow surface concave relative to the image surface, or a concave face of a concave lens, which can form the first optical group or be a part of this group. The concave lens is preferably arranged upstream of the pupil surface, and the concave face points toward the pupil surface. A surface distance d of the concave face from the pupil surface should preferably be dimensioned such that the condition $0 < d/DP < 2$ is fulfilled for a ratio d/DP between the surface distance d and an optically free diameter DP in the pupil surface. The optically free diameter is frequently determined by an aperture diaphragm arranged in the region of the pupil surface near the image. For systems with an intermediate image, in particular in the case of catadioptric systems with an intermediate image, it can also be a conjugate image of the aperture diaphragm when the latter is seated, for example, in the region of the concave mirror or is formed by the edge thereof. The aperture diaphragm should in this case be arranged such that the wafer space is substantially telecentric.

[0024] In preferred embodiments, the concave lens is a meniscus lens. The concave lens preferably has negative refractive power.

[0025] In some embodiments, the concave face has a radius of curvature R that is of the order of magnitude of the surface distance d of the concave face from the pupil surface. Such a concave face is denoted as "substantially concentric with the pupil surface" when the condition $0.5 * R < d < 1.5 * R$ is fulfilled. The satisfaction of this condition permits systems in which effective correction of the sine condition in the image

plane is not only given for axial field points but is found to be substantially constant over the entire field. It is thereby possible for large fields to be exposed with high imaging quality even for high apertures.

[0026] For some embodiments, the spherically undercorrecting second optical group comprises at least one positive lens. It is preferred to provide a biconvex positive lens whose entrance side should be more strongly curved than its exit side.

[0027] This renders possible overall radiance transformation groups that are constructed with very few lenses. The radiance transformation group preferably comprises only two lenses, something which is advantageous for the overall transmission of the system because of the low number of surfaces, and can contribute to a structure of low mass.

[0028] According to the invention, projection objectives can be rotationally symmetrical systems of purely refractive design. Effective color correction can also be achieved at very low wavelengths with the aid of catadioptric projection objectives, it being possible here, in turn, for catadioptric projection objectives with geometric beam splitting and real intermediate image to be favorable. Measures are represented below that permit such systems to be constructed with a compact design and an outstanding state of correction.

[0029] In accordance with one embodiment, a catadioptric projection objective is provided that serves for projecting a pattern of a mask arranged in an object plane of the projection objective into an image plane of the projection objective with the production of a real intermediate image. The projection objective comprises:

a catadioptric first objective part that is arranged between the object plane and the image plane and has a concave mirror and a beam deflecting device; and

a second objective part, which is arranged between the first objective part and the object plane,

the beam deflecting device having a fully reflecting first folding mirror with a flat reflecting surface that defines a first reflecting plane that is inclined relative to an object plane segment of the optical axis perpendicular to the object plane and intersects the object plane segment at a mirror distance c from the object plane; and

an object field of the projection objective being arranged eccentrically relative to the object plane segment in such a way that an object field distance b exists between the object plane segment and the object field;

and the condition:

$$1 \leq P1 \leq 1.9 \qquad (1)$$

is observed, where $P1 = \frac{c}{b} \cdot \tan(\arcsin(NA \cdot |\beta|))$, NA is the image-side numerical aperture, and β is the magnification ratio of the projection objective.

[0030] It has proved to be particularly advantageous when the parameter P1 assumes values between approximately 1.2 and 1.8, in particular between approximately 1.4 and 1.6.

[0031] The inventors have found out that in the case of a catadioptric projection objective with a geometric beam splitter and intermediate image an optimum compromise between the size of the superfield to be corrected, on the one hand, and a suitable design of the projection objective, on the other hand, is possible for the targeted, very high image-side numerical apertures given satisfaction of the specified boundary conditions for the parameter P1. The parameter P1 describes a region of optimum relative positions of the off-axis object field, on the one hand, and of the

first folding mirror, on the other hand, in order to achieve imaging free from vigneting in conjunction with the smallest possible superfield size for a given magnification β and image-side numerical aperture NA.

[0032] Upon undershooting of the lower limiting value (P1 = 1), it would be necessary (for a given NA) for the object field distance b to be enlarged to unfavorably high values in order still to ensure imaging free of vigneting for a given mirror position. It is to be borne in mind here in the case of systems with h-folding, for example, that imaging free from vigneting requires, on the one hand, that the beam coming from the object field can pass the first folding mirror on the way to the concave mirror without lateral cropping, and that, on the other hand, the first folding mirror is still to be positioned so favorably that the radiation coming from the concave mirror fully strikes the first folding mirror in order to be deflected without vigneting in the direction of the image plane. However, excessive enlargement of the object field distance b would lead to a large "superfield", and this complicates the optical correction of the overall system.

[0033] Upon overshooting of the upper limit (P1 = 1.9), it would certainly be possible to keep low the object field distance b, and thus the superfield diameter to be corrected. However, with the approach of the object field into the object field section of the optical axis, the intermediate image would also approach the corresponding section of the optical axis. This would consequently necessitate likewise bringing the first folding mirror, which is typically arranged in the vicinity of the intermediate image, close to the optical axis. This is possible only to a limited extent without introducing vigneting of the beam in the light path from the object field to the concave mirror, or from the concave mirror to the image plane.

[0034] The invention renders it possible to create projection objectives for which the geometric photoconductance to be corrected does not become too large even given very high numerical apertures. Here, the geometric photoconductance (or etendue) is defined as a product of the image-side numerical aperture and the field size. It has proved to be advantageous when a diagonal ratio a between the length of the diagonal of a minimum circle (superfield diagonal) centered on the optical axis and enclosing the object field and the length of a diagonal of the object field is smaller than 1.5 times the image-side numerical aperture NA of the projection objective. In the case of wafer scanners with a rectangular object field with the narrowness of a slit, the diagonal of the object field can also be denoted as a slit diagonal.

[0035] In advantageous embodiments of projection objectives according to the invention, no lens or lens group with a refractive power $D = 1/|f|>1m^{-1}$ is provided in an installation space between the object plane and the first folding mirror, f being the focal length of the lens or lens group. It is preferable for no lens at all to be arranged in the installation space between the object plane and the first folding mirror. It is thereby possible for the first folding mirror to be moved up close to the object plane. This enables embodiments for which the mirror plane distance c is smaller than 10% or 5% of the overall length of the projection objective. It is possible thereby for the beam deflecting device, which can also be denoted as deflecting module, to be of particularly compact configuration. Some embodiments have only a plane-parallel transparent plate as optical component closest to the object field in the space between the object plane and deflecting module.

[0036] The measures described can be used for catadioptric projection objectives with geometric beam splitting and different folding geometries. In one development, the first folding mirror is arranged in the beam path between the concave mirror and the image plane. The first folding mirror is thereby typically situated on the side of the object plane segment of the optical axis facing the concave mirror. Without further folding mirrors, the object plane and the image plane would then be arranged at an angle to one another, for example perpendicular to one another. It is favorable when a second folding mirror is provided for deflecting the radiation coming from the first folding mirror in the direction of the image plane, the second folding mirror preferably being arranged such that an image plane segment of the optical axis defined between the second folding mirror and image plane runs parallel to the object plane segment of the optical axis. A parallel arrangement of object field and image field is thereby possible. A transverse segment of the optical axis running transverse to the object plane segment and to the image plane segment is then defined between the first folding mirror and the second folding mirror. The associated part of the objective is also denoted below as "horizontal arm (HOA)".

[0037] It has proved to be favorable when at least one lens or lens group is arranged between the first folding mirror and the second folding mirror, for example in the region of the transverse segment. The refractive power thereby provided can be used, inter alia, for optimizing the beam path between the folding mirrors, and for the optical correction. In particular, positive refractive power can be arranged between the first and second folding mirrors. The overall size of the optical components following the transverse segment, that is to say the overall size of the second folding mirror and the lenses following thereupon, can thereby be kept small.

[0038] In order to be able to use the advantages of the arrangement of lenses between the first and second folding mirrors without having to accept disadvantages possibly resulting therefrom with reference to the design and stability of the arrangement, it is provided in the case of some embodiments that a total lens mass m_{HOA} of lenses between the first and the second folding mirror is less than 15% of the total lens mass m_{GES} of the projection objective, less than 10% being achieved for some embodiments.

[0039] Particularly in the case of embodiments for which one or more lenses are arranged between the first folding mirror and the second folding mirror, it can be advantageous when the first folding mirror is inclined with reference to the object plane segment of the optical axis such that an angle of mirror inclination of more than 45° is enclosed between the reflecting plane and the object plane segment. The deviation from a 45° inclination should be substantially above the deviation caused by manufacturing tolerances, and can be in the region between 1° and 10°, for example. In preferred embodiments, the angle of mirror inclination is between 47° and 55°. As a result, the segment of optical axis that follows in the first folding mirror is inclined away from the object plane and can run obliquely to the horizontal direction in the installed state. It is thereby possible for lenses or other optical elements to be positioned in this inclined segment without their mounts reaching disturbingly into the region of the reticle holder.

[0040] The setting of a suitable magnification ratio for that objective part that produces the intermediate image can be used to optimize the system properties. An objective segment arranged between the object plane and intermediate image preferably has a magnification ratio β_{IMI} for which it holds that $0.95 \leq |\beta_{IMI}| \leq 1.2$. It is

favorable when $|\beta_{IMI}|$ is in the vicinity of 1, for example between 0.98 and 1.1. Nevertheless, it is possible with some embodiments to achieve the result that the intermediate image is situated in the vicinity of the first folding mirror, which has a certain spatial distance from the object plane. In particular, the intermediate image can be arranged in the optical path between the concave mirror and the first folding mirror.

[0041] It can be advantageous, moreover, when the numerical aperture NA_{IMI} at the intermediate image is comparable to the object-side numerical aperture NA_O at the object plane. It preferably holds that $NA_{IMI} \le NA_O$, that is to say the numerical aperture at the intermediate image should not be greater than that in the object plane.

[0042] With projection objectives, it is customary to provide a system aperture with a variable aperture diameter for limiting the cross section of the radiation passing through the projection objective. This can be arranged in the region between the intermediate image and image plane. In some embodiments, however, the system aperture is arranged in the catadioptric objective part. In some embodiments, this objective part has relatively few lenses and other optical components, which are frequently arranged at relatively large distances from one another. This is attended by favorable possibilities for positioning a system aperture, and there is no need for the design of the objective in the region near the image field to be configured such that an adequate distance remains between suitable lenses for the purpose of positioning a variable system aperture. A system aperture in the catadioptric objective part therefore creates design freedoms in the second, as a rule dioptric or refractive, objective part, whose lenses can be optimally fashioned and positioned with regard to their optical effect. Although this is a

flat system aperture in the case of which the aperture edge remains independent of the aperture diameter set in a plane, in some embodiments it is provided that the system aperture has an aperture edge that determines the aperture diameter and whose axial position can be varied with reference to the optical axis of the projection objective as a function of the aperture diameter. This may be a displaceable aperture.

[0043] It is also possible for the aperture diaphragm or system aperture to be designed as a conical aperture or spherical aperture such that the aperture edge can be moved along a conical surface or along a spherical surface or the surface of an ellipsoid during adjustment of the aperture diameter. This is particularly favorable when the system aperture is positioned in the vicinity of the concave mirror, since in this case the aperture edge can always be kept in the vicinity of the mirror contour, and this minimizes vigneting.

[0044] The invention permits the provision of projection objectives that can be effectively corrected and can achieve very high numerical apertures in conjunction with a compact design and a finite image-side working distance of sufficient magnitude. In particular, the image-side aperture can be at NA > 0.75, NA > 0.8 or NA > 0.9 being possible, and being achieved in some embodiments.

[0045] In addition to emerging from the claims, the above features and further ones also emerge from the description and from the drawings, it being possible for the individual features to be implemented on their own or separately in the form of subcombinations in an embodiment of the invention and in other fields, and for them advantageously to constitute embodiments inherently capable of protection.

[0046] Figure 1 shows a lens section through an embodiment of the projection objective according to the invention and with an h-folding geometry;

Figure 2 shows a lens section through a segment, near the image field, of a projection objective according to the invention, with beams of an axial field point for the purpose of explaining the action of the optical means for correcting the sine condition;

Figure 3 shows the lens section from figure 2 with beams of a field edge point for the purpose of explaining the action of the optical means for correcting the sine condition;

Figure 4 shows a schematic illustration of the dimensioning of the object field and superfield in the object plane of the projection objective; and

Figure 5 shows a schematic of the beam path in the region between the object plane and first folding mirror.

[0047] In the following description of preferred embodiments, the term "optical axis" denotes a straight line or a sequence of straight line segments through the centers of curvature of the optical components. The optical axis is folded at folding mirrors (deflecting mirrors) or other reflecting surfaces. Directions and distances are described as "image-side" when they are directed in the direction of the image plane or of the substrate to be exposed that is located there, and as "object-side" when they are directed with reference to the optical axis toward the object plane or toward a reticle located there. In the examples, the object is a mask (reticle) with the pattern of an integrated

circuit; it may also be another pattern, for example a grating. The image is projected in the examples onto a wafer provided with a photoresist layer and which serves as substrate. Other substrates, for example elements for liquid crystal displays or substrates for optical gratings, are also possible.

[0048] Figure 1 shows an embodiment of a catadioptric reduction objective 1 according to the invention, with geometric beam splitting. It serves the purpose of imaging on a reduced scale, for example in the ratio 4:1, a pattern of a reticle or the like arranged in its object plane 2 into an image plane 4 situated parallel to the object plane 2, doing so with the production of a single real intermediate image 3. Between the object plane 2 and the image plane 4, the objective 1 has a catadioptric objective part 5 with a concave mirror 6 and a beam deflecting device 7, and a dioptric objective part 8 that follows the catadioptric objective part and includes only refractive optical components.

[0049] Since the reduction objective produces a real intermediate image 3, two pupil planes 10, 11 are present, specifically a first pupil plane 10 in the catadioptric objective part 5 immediately upstream of the concave mirror 6, and a second pupil plane 11 in the region of large beam diameter in the dioptric objective part 8 in the vicinity of the image plane 4. The main beam of the image crosses the optical axis 12 of the system in the regions of the pupil planes 10, 11. The pupil planes 10, 11 are aperture locations that are optically conjugate to one another, that is to say preferred locations in the region of which a physical aperture for limiting the beam cross section can be positioned. In the exemplary system, a system aperture 12 of variable aperture diameter is arranged in the refractive part near the pupil surface 11. In other embodiments, an adjustable system diaphragm is seated in the region of the pupil surface 10 immediately

upstream of the concave mirror. This system aperture can be configured, in particular, as a conical aperture or as a spherical aperture.

[0050] The beam deflecting device 7 has a first folding mirror 20 with a highly reflective, flat reflecting surface, and is arranged obliquely in the beam path between the concave mirror 6 and the image plane 4 in such a way that it can deflect the radiation coming from the concave mirror 6 in the direction of the image plane. Located in the beam path between the first folding mirror and the image plane at a larger distance downstream of the first folding mirror is an obliquely positioned second folding mirror 21 of larger diameter that likewise has a flat, highly reflective reflecting surface and serves the purpose of deflecting the radiation coming from the first folding mirror in the direction of the image plane. Because of the h-shape of the overall arrangement, this folding geometry is also denoted as h-folding.

[0051] The optical axis of the system is multiply folded, and comprises an object plane segment 25 that is perpendicular to the object plane 2 and runs through the center of curvature of the concave mirror, a transverse segment 26, situated between the first and second folding mirrors, that includes in the example an angle of approximately 170° with the object plane segment, and an image plane segment 27, running parallel to the object plane segment 25, that is perpendicular to the image plane and runs through the centers of curvature of the lenses situated downstream of the second folding mirror.

[0052] Whereas the first folding mirror 20 is optically necessary in order geometrically to separate the radiation running toward the concave mirror from the radiation coming from the concave mirror, the second folding mirror 21 can also be eliminated. The object

plane and the image plane would then be at an obtuse angle to one another without further reflecting mirrors. By contrast, the second folding mirror 21 produces a parallel position of the object plane and image plane that is favorable for scanner operation of the projection machine comprising the projection objective. Moreover, the arrangement permits all the lenses, apart from the lenses arranged in the transverse segment, and the concave mirror to be held with a vertical optical axis and, therefore, in a largely stable fashion against gravity-induced external influences.

[0053] As may be seen in figure 1, starting from an illumination system (not shown) on the side of the object plane 2 averted from the image, the light enters the projection objective and firstly penetrates upstream thereof the mask arranged in the image plane and having the pattern to be projected, for example the pattern of an electric circuit or a semiconductor memory element. The transmitted light then penetrates a plane-parallel plate 30 that seals off the projection objective hermetically on the object side. Without striking the first folding mirror, the expanding beam then strikes a biconvex positive lens 31 which is followed at a distance by a negative meniscus lens 32 with a concave face on the object side. The light runs onto a mirror group that comprises the concave mirror 6 and two negative meniscus lenses 33, 34 positioned immediately in front of said concave mirror and whose surfaces are respectively curved relative to the concave mirror 6 and have the same sense of curvature as the concave mirror. The light reflected by the concave mirror 6 now runs convergently in the direction of the first folding mirror, the negative lenses 34, 33 near the mirror, the negative meniscus 32 and the strong positive lens 31 being traversed twice.

[0054] The intermediate image 3 that is projected into the image plane 4 with the aid of the downstream lenses

35 to 47 of the dioptric, second objective part 8 is formed immediately upstream of the first folding mirror in the direction in which the light runs. In this case, the first step is for a positive/negative doublet with a biconvex positive lens 35 and a downstream negative meniscus lens 36 with an object-side concave face to be traversed, these lenses arranged near the field having small diameters. Following thereafter at a distance is a biconvex positive lens 37 ahead of when the light is deflected anew at the second folding mirror 21. The lenses 35, 36 and 37 in the transverse segment 26 between the folding mirrors are also denoted below as "horizontal arm lenses" or "HOA lenses", although the optical axis 26 does not run horizontally here, but obliquely downward, thereby ensuring that the parts of the mount for the horizontal arm lenses do not project into the reticle space.

[0055] Following downstream of the second folding mirror 21 is a negative/positive doublet with a negative meniscus lens 38 that is concave relative to the image plane, and a following biconvex positive lens 39. Following thereafter at a distance in the virtually collimated beam path immediately upstream of the pupil surface 11 is a strongly curved negative meniscus lens 40 with an image-side concave face at which very high angles of incidence of the penetrating radiation of more than 60° occur. Following after the pupil surface 11 or the system aperture 12 as a lens of very large diameter is a biconvex positive lens 41 that is followed by a negative meniscus lens 42, which is arranged in the convergent beam path and is concave relative to the image plane 4, and a biconvex thick positive lens 43 following said negative meniscus lens. The radiation, which is already strongly convergent thereafter, is further combined by means of two positive meniscus lenses 44, 45, which are concave relative to the image plane 4, before they penetrate a virtually planoconvex positive lens 46 and a relatively

thick plane-parallel end plate 47 that is seated upstream of the image plane 4 at a slight working distance.

[0056] Table 1 summarizes the specification of the design in tabular form. Here, column 1 specifies the number of the surface, which is refracting, reflecting or labeled in some other way, and column 2 labels special surfaces with the aid of abbreviations for which it holds: R = reticle = object plane, CM = concave mirror, IMI = intermediate image, M1 = first folding mirror, M2 = second folding mirror, AS = system aperture, W = wafer = image plane. Column 3 specifies the type of surface (sphere/asphere), column 4 the radius r of the surface (in mm), column 5 the distance d, denoted as thickness, of the surface from the downstream surface (in mm), column 6 the material of the component, and column 7 the optically useful, free diameters of the optical components (in mm). Column 8 specifies the values sin i_{max} for the maximum sine of the angle of incidence at the corresponding surface.

[0057] Let the "sine of the angle of incidence" of a beam at a surface be the product $n \cdot \sin(i)$ of the refractive index n of the medium situated in the direction of the light upstream of the surface and the sine of the angle of incidence i. Here, the angle of incidence is the angle that is enclosed by the light beam and the surface normal at the point of impingement. Let the "maximum sine of the angle of incidence" at a surface be the maximum of the sine of the angle of incidence over all light beams impinging on this surface.

[0058] The overall length L of the dry objective between the object plane and image plane along the optical path on the optical axis is approximately 2812 mm. The projection objective is designed for an operating wavelength of approximately 157 nm at which the lens material of calcium fluoride used for all the

lenses has a refractive index of n = 1.5841. The free working distance is 6 mm on the image side. The image-side numerical aperture NA is 0.95. An off-axis field of size 26 mm · 5.5 mm (4.5 mm off-axis) can be exposed on the image side or wafer side. The system is doubly telecentric and has a magnification ratio of 4:1. The projection objective can be operated with the aid of an F_2 excimer laser whose bandwidth is (FWHM) ≤ 1.5 pm. Catadioptric systems of such design can resolve structures with critical dimensions CD ≤ 50 nm.

[0059] Ten of the surfaces in the system are aspheric, the aspheric surfaces 7 and 17, and 9 and 15, respectively, in Table 1 being traversed twice. Table 2 specifies the corresponding aspheric data, the sagittas of aspheric surfaces being calculated using the following rule:

$$p(h)=[((1/r)h^2)/(1+SQRT(1-(1+K)(1/r)^2h^2)]+C1*h^4+C2*h^6+...$$

[0060] Here, the reciprocal (1/r) of the radius specifies the surface curvature at the surface apex, and h specifies the distance of a surface point from the optical axis. Consequently, p(h) gives this sagitta, that is to say the distance of the surface point from the surface apex in the z-direction, that is to say in the direction of the optical axis. The constants K, C1, C2 ... are reproduced in Table 2.

[0061] For at most half of the aspheres, the maximum aspheric sagitta is greater than 300 μm, thus facilitating the production and testing of the aspheres. The number of lenses (17 here) is very small, and this permits a design of low mass with effective transmission. Preferred embodiments have less than 20 refractive components conserving refractive power.

[0062] Further special features of these and other embodiments of the invention are explained in more detail in conjunction with figures 2 and 3. The figures

respectively show the rear part of the dioptric second objective part 8, which follows the second folding mirror 21. Shown in each case for the purpose of explaining the optical action of the lenses of this part are the courses of twenty rays that emanate in figure 2 from a point of the object field lying on the optical axis, and emanate in figure 3 from a point lying at the edge of the object field. The rays used for the illustration represent rays that are equidistantly arrayed in the object space, that is to say on the object plane, with reference to their direction cosine. The direction cosine of a ray is understood here as the sine of the angle between the ray and the optical axis. An equidistant or uniform array signifies that the direction cosines of two neighboring, depicted rays differ in each case by a constant. This state is denoted here as "uniform angular radiance". Consequently, the geometric density, illustrated in the drawing, of the rays represents an "angular radiance", that is to say the radiance in angular space.

[0063] In the case of small numerical apertures such as normally occur in the region of the object field, the beam angles are relatively small, and consequently the beam angles themselves are arrayed quasi-equidistantly. If, by contrast, the geometric beam angles of the rays going to the pupil edge (edge rays) are large, the geometric beam angles appear to be in a coarser array in the illustration toward the edge of the pupil than in the middle of the pupil.

[0064] If an array of rays with equal absolute angular distances between neighboring rays were chosen, the illustration would look very similar in principle, since relatively low values of the numerical aperture of the radiation are present in the left-hand region of the objective part shown and in the entire region upstream of this part, and so equal increments of the

absolute values of the beam angles appear substantially equal like equal increments in the direction cosine.

[0065] Considering now the course of the rays and of the angular radiance thereof represented by the density of neighboring rays, it is a striking fact that there is a relatively uniform angular radiance independent of the beam height (the distance between the rays and the optical axis) upstream of the strongly curved meniscus lens 40 that is hollow toward the pupil 11. By contrast, there is a very nonuniform angular radiance downstream of the biconvex positive lens 41 following the pupil plane, the angular radiance depending in this region on the beam height and decreasing with increasing beam height, that is to say with increasing distance from the optical axis. This effect is particularly strongly pronounced toward the edge of the pupil.

[0066] It is therefore evident that the ray spacing from the edge of the pupil in no way rises so strongly on the object side as on the image side, since the numerical aperture and thus the geometric beam angles are substantially smaller on the object side.

[0067] In the embodiment shown, this transformation of the angular radiance is essentially effected by the strongly curved meniscus 40 upstream of the pupil surface, and the biconvex positive lens 41 immediately following the pupil surface. These lenses form a radiance transformation group 100 whose resulting output radiance distribution is converted into an angular radiance distribution in the image plane 4 by the downstream aperture-generating group 200, which is formed by the lenses 42 to 47. The lenses of the aperture-generating group are substantially responsible in this case for the high image-side numerical aperture.

[0068] The radiance distribution produced by the radiance transformation group 100 is adapted to the beam guidance properties of the aperture-generating group 200 such that the sine condition is substantially fulfilled in the image plane 4 for all the beams of the input light distribution. This is to be seen in an essentially uniform angular radiance at the image plane. This, in turn, may be detected in the figures by virtue of the fact that the penetration points of the beams at the flat, last optical surface of the objective, specifically on the exit side of the end plate 47, are strongly non-equidistant. The correction of the sine condition is essential for a high imaging quality and signifies that the optical system has the same magnification ratio for all the zones of its cross section.

[0069] The inventors have found that an optical system that converts a space with a relatively low numerical aperture into a space with a relatively high numerical aperture should carry out such a radiance transformation when the sine condition is to be fulfilled. In this case, a region of relatively uniform angular radiance should be transformed into a region of nonuniform angular radiance that decreases toward the edge of the beam. This effect is more strongly pronounced in the case of very high numerical apertures, and is very important there in order to achieve a very high imaging accuracy.

[0070] In the case of the embodiment, the ray spacing, which becomes larger on the image side toward the edge, is produced with the aid of the radiance transformation group 100 from a ray spacing that is, rather, equidistant. For this purpose, a specific spherical aberration is firstly introduced at a suitable distance upstream of the image plane. This purpose is served in essence by the meniscus lens 40, which has a spherically strongly overcorrecting action, and can

also be replaced in the case of other embodiments by an optical group with a number of lenses, or by a differently shaped lens. Propagation of the spherical aberration sets the offset of the correction of the sine condition in the aperture space. The aperture space itself, that is to say the region of the pupil surface 11, is plainly not corrected for sine, by contrast. Particularly in the edge region, on its spherical exit surface the meniscus 40 has very large angles of incidence that lead to a strong change in the beam angle spacing over the aperture. When the rays finally reach the entrance surface of the downstream positive lens 41, a highly nonuniform angular radiance distribution has already been set up.

[0071] However, in order to achieve good imaging it is not sufficient merely to fulfill the sine condition in the image plane. Theoretically, it is possible to design systems with a sine condition that is perfectly satisfied, but which have a large fraction of spherical aberration in the image plane. However, since the spherical aberration should also be effectively corrected, provision is made of the downstream, spherically undercorrecting positive lens 41 that compensates the majority of the spherical aberration produced by the meniscus lens 40. This results at the exit of the biconvex lens 41, that is to say at the exit of the radiance transformation group 100, in a nonuniform distribution of the angular radiance with angular radiance that decreases toward the edge, but with only a little spherical aberration. The downstream lenses of the aberration-generating group are required for providing the high numerical apertures in the image plane. They influence essentially aberrations of higher order. However, the most important transformation has already been performed by the radiance transformation group 100 at a large distance upstream of the image plane.

[0072] It is possible to use aspheres for this transformation. However, it has proved to be very advantageous to use at least one concave lens with a strongly curved concave face at which there occur high angles of incidence whose sine can preferably have more than 80% or more than 90% of the image-side numerical aperture of the projection objective.

[0073] A further special feature is explained in conjunction with figure 3, in which off-axis rays from the edge of the field are shown. It is to be noted here that the concave exit surface of the meniscus 40 at which the high angles of incidence occur is situated in a fashion substantially concentric with the position of the pupil surface 11. A surface distance d of the concave face (measured along the optical axis toward the apex of the surface) should preferably have a value of the order of magnitude of the radius of curvature R and, for example, in the range between 0.5 * R and 1.5 * R. It is possible to achieve thereby that the radiance transformation described can be achieved in a relatively constant fashion for all the rays of the entire field. This contributes to achieving imaging with very few aberrations over large field sizes in conjunction with very high numerical apertures.

[0074] The surface distance d of the concave face from the downstream pupil surface 11 should be dimensioned such that a ratio d/DP between this surface distance and an optically free diameter DP in the pupil surface is between zero and two. In the case of the example, this value is between approximately 0.5 and 1. It is therefore necessary to target an arrangement of the concave face near the aperture.

[0075] Projection objectives according to the invention take account of the fact that in addition to the customary correction of aberration it is also necessary to provide means for correcting the sine condition when

correcting high-aperture projection systems for microlithography having a finite working distance in air. This correction of the sine condition becomes increasingly more difficult with the size of the working distance, and is effected in the case of the system of the invention by the correction means explained above. Were an objective in immersion to be considered, given the same numerical aperture the geometric beam angle in the image space would be substantially smaller, and the effect would be substantially reduced by comparison with dry systems. However, correction means of the type presented here can also be used advantageously in principle in immersion systems.

[0076] Further special features of these and other embodiments of the invention are explained in more detail in conjunction with figures 4 and 5. Because of the geometric beam splitting, the projection objective has an object field 50 that is arranged off-axis, and so between the object field segment 25 of the optical axis and the object field 50 there is a finite object field segment b that amounts to 18 mm in the embodiment shown. The object field of the wafer scanner is rectangular or slit-shaped with a high aspect ratio, and is characterized by the length of its diagonal 51 (slit diagonal), which measures approximately 26.2 mm in the example. In order to be able to image this off-axis object field with low aberration, it is necessary to correct the projection objective for a field size that is substantially larger than the object field. This circular superfield 52, which is surrounded by a minimum circle, centered around the optical axis 25, around the eccentric object image, can be defined by the length of its diagonal 53, which is denoted here as superfield diagonal and measures 32.8 mm in the exemplary system. It is to be seen by the person skilled in the art that the diagonal ratio a between the length of the superfield diagonal and the length of

the slit diagonal should be as close as possible to 1 in order to have the lowest possible outlay on correction in the case of the off-axis object field. It has emerged that it is favorable when the diagonal ratio a is less than 1.5 times the image-side numerical aperture NA, something which can be regularly fulfilled with projection objectives according to the invention. In the case of the example, it holds that a = 1.23, whereas for NA = 0.95 the limit (1.5 · NA) is at 1.425.

[0077] A number of measures can contribute alternatively or cumulatively to optimizing the size of the superfield in the case of projection objectives according to the invention. Figure 5 may firstly be used to illustrate in detail the geometry of beam and design for a projection objective in accordance with figure 1 in the region between the object plane and first folding mirror. The first folding mirror 20 is arranged at a distance next to the object plane segment 25 of the optical axis, and inclined thereto by the angle of mirror inclination γ of approximately 50°. A reflecting plane 20′ defined by the flat reflecting surface intersects the object plane segment 25 at a reflecting plane distance c from the object plane. The radiation emanating from the off-axis object field 50 may be characterized with the aid of a beam 60 that emerges at the edge of the object field facing the axis. The (lower) coma ray 61 of the beam that faces the axis runs at an angle α to the optical axis 25, the sine of this angle corresponding to the object-side numerical aperture NA_O of the projection objective, which is, in turn, the product of the image-side numerical aperture NA and the magnitude of the magnification β of the projection objective (β = 0.25 in the example). The lower coma ray 61 intersects the inner object segment 25 at a distance d of the point of intersection of the ray from the object plane. It holds

that: $\tan\alpha = \frac{b}{d}$. Consequently, the parameter P1 in equation (1) corresponds to the ratio c:d.

[0078] It may be seen that for a given object field distance b the image-side numerical aperture (represented by α) cannot be arbitrarily enlarged for a given position of the folding mirror 20, without the lower coma ray 61 being cropped at some time, that is to say without vigneting occurring.

[0079] It is likewise directly to be seen that for a given numerical aperture and mirror position it is possible for the object field distance b to be reduced only to the extent that the coma ray 61 can still pass the first folding mirror 20 without being cropped (vignetted).

[0080] It is further to be noted that the first folding mirror 20 cannot be moved arbitrarily close to the object plane segment 25, since it has to be ensured that all the light coming from the intermediate image 3 strikes the folding mirror and is deflected. This is also noted when the object field segment b is to be reduced, since in this case the intermediate image likewise moves toward the optical axis 25, and so it can happen that some of the radiation coming from the intermediate image no longer strikes the first folding mirror.

[0081] Taking account of these relationships, the abovementioned range for the parameter P1 has proved to be particularly favorable. This can also be expressed in such a way that the distance d of the point of intersection of the ray is preferably to be in the range between c/1.9 and c. In one limiting case (c = d), the coma ray 61 would intersect the object plane segment 25 precisely at the point of intersection of the reflecting plane 20′ with this part of the

optical axis. If d were to be further enlarged starting therefrom, it would be necessary for a given numerical aperture to enlarge the object field distance b, and thus the superfield, in order to avoid vigneting at the first folding mirror. If the other limit of the parameter range is exceeded (d < c/1.9) it is then certainly possible to reduce the object field distance b and thus the superfield size, but this would finally lead to vigneting at the mirror for a given NA. Furthermore, the reduction of b would lead to a reduction in the lateral distance between the intermediate image and optical axis. It would certainly be possible under these conditions to avoid the vigneting on the beam path from the object field to the concave mirror were the first folding mirror to be moved away from the optical axis 25, but there would then be the risk of all the light coming from the intermediate image no longer striking the first folding mirror, thus giving rise to vigneting. The said parameter range is therefore optimum for P1.

[0082] A further special feature of the system consists in that a number of lenses are arranged in the transverse segment between the folding mirrors 20, 21, which is also denoted as "horizontal arm". It has been shown that the arrangement of positive refractive power is very favorable in this range in order to achieve numerical apertures of more than NA = 0.75, the advantages increasing with increasing NA. On the other hand, for mechanical reasons and reasons to do with installation space, it must be ensured that use is made in this range of a minimum number of lenses which have minimal free diameters. Minimal diameters in this range are favored in this embodiment by virtue of the fact that the magnification ratio β_{IMI} between the object plane and intermediate image is very close to 1 (here $\beta_{IMI} = 0.99$). This magnification ratio is possible, inter alia, by virtue of the fact that no positive refractive power is arranged between the object plane

and the beam deflecting device 7 in the installation space. Nevertheless, the intermediate image is in the vicinity of the first folding mirror, specifically preferably in the optical path upstream thereof. As a result, the numerical aperture of the radiation at the intermediate image is comparable to the numerical aperture NA_0 at the object plane. In particular, it is not larger than the object-side numerical aperture. It is thereby possible to achieve that the beam cross section downstream of the intermediate image rises only moderately in the horizontal arm such that it is possible to make use in this region of lenses with small diameters.

[0083] In conjunction with the small diameters, the small number of less than six or five or four, specifically only three lenses in the transverse segment has the effect that the mass of these lenses remains limited. In the embodiment shown, the total lens mass of the HOA lenses 35, 36, 37 is only 7.3 kg, and thus only 8.4% of the lens mass of the overall system.

[0084] The approximate 1:1 projection between the object plane and intermediate image therefore assists in arranging in the region of the horizontal arm downstream of the intermediate image lenses that promote the attainment of very high numerical apertures and at the same time contribute to keeping the diameters of the downstream lenses low by means of a collecting effect overall. On the other hand, the aim should be for the intermediate image to be situated in the vicinity of the first folding mirror, in order to permit deflection free from vigneting in conjunction with compact mirror sizes. Nevertheless, a distance must remain between the object plane and beam deflecting device or folding mirror despite the approximate 1:1 projection. In other words: the intermediate image is to be situated geometrically

closer to the concave mirror than to the object plane. The fulfillment of these conditions is promoted by the provision of the positive lens 31 immediately preceding the intermediate image. Its strongly positive refractive power makes a substantial contribution to the fact that the beam path is virtually telecentric not only in the region of the object plane, but also in the region of the intermediate image. It is possible as a result of this for the intermediate image to be displaced in the direction of the concave mirror from a position that is symmetrical with regard to geometry despite an approximate 1:1 projection. It is thereby possible for the reticle plane or object plane 2 and the region of the intermediate image 3 to be separated from one another spatially despite a favorable 1:1 magnification ratio.

[0085] It is worthy of note in the case of the lenses of the transverse segment between the folding mirrors that the doublet 35, 36 that is arranged in the field vicinity near the intermediate image and opens up with a spherical entrance surface has a very low refractive power overall. The lenses of the doublet substantially serve the purpose of correcting monochromatic aberrations, chiefly distortion. This near-field correction of aberration permits the region immediately downstream of the object plane to be kept free from lenses. The positive lens 37 arranged in the case of relatively large edge ray heights directly upstream of the second folding mirror serves the purpose chiefly of deflecting the main beam such that a favorable location of the aperture is produced in the downstream objective part. The positive refractive power is optimized such that, on the one hand, the diameters of the downstream lenses remain moderate (the positive refractive power may not be too weak for this purpose) and, on the other hand, the position of the image plane 4 in the vertical direction is far below the position of the concave mirror 6 so that the units serving the purpose of wafer

manipulation can be constructed and used without being impeded by the concave mirror.

[0086] The risk of optical components projecting from the transverse segment in the reticle space exists because of the first folding mirror 20 being arranged geometrically in the vicinity of the object plane and because of the use of lenses in the transverse segment. This risk results from an oblique position of the transverse arm or of the transverse segment 26. Depending on the embodiment, an angle of between approximately 5° and approximately 20° can be favorable between the direction of the transverse segment and a horizontal direction running perpendicular to the object plane segment.

[0087] It has proved to be very advantageous for the optical correction when a maximum angle of incidence of more than 60° occurs in the interior of the projection system at at least one optical surface. It is particularly favorable when such a surface occurs in the vicinity of a pupil plane. Arranged immediately upstream of the pupil surface 11 in the exemplary embodiment is the negative meniscus lens 40, which has a concave face of strong curvature directed toward the pupil surface and forms the exit face of the meniscus lens. The maximum sine of the angle of incidence at this surface is 0.94, and thereby corresponds substantially to the image-side numerical aperture of the system. It is favorable in general when at least one such concave face is provided for which the maximum sine for the angle of incidence of the penetrating radiation is larger than approximately 80%, in particular larger than approximately 90% of the image-side numerical aperture of the projection objective.

Table 1

No.	Label	Type	Radius	Thickness	Material	Free diameter	sinimax
0	R	Sphere	plane	38,000			
1		Sphere	plane	0,000		146,380	0,2375
2		Sphere	plane	10,000	'CAF2-UV'	146,380	0,2375
3		Sphere	plane	221,457		148,973	0,2375
4		Sphere	415,903457	58,422	'CAF2-UV'	256,692	0,541
5		Sphere	-371,093936	96,343		257,394	0,5371
6		Sphere	-239,955213	20,000	'CAF2-UV'	225,035	0,6492
7		Asphere	-684,567176	284,664		231,349	0,2239
8		Sphere	-232,206117	15,000	'CAF2-UV'	243,448	0,5231
9		Asphere	-526,015163	40,350		258,092	0,1308
10		Sphere	-249,074443	15,000	'CAF2-UV'	266,071	0,3853
11		Sphere	-1283,07641	69,547		298,059	0,5002
12	CM	Sphere	-313,718622	-69,547		332,055	0,0786
13		Sphere	-1283,07641	-15,000	'CAF2-UV'	298,636	0,5247
14		Sphere	-249,074443	-40,350		265,388	0,3406
15		Asphere	-526,015163	-15,000	'CAF2-UV'	255,846	0,1844
16		Sphere	-232,206117	-284,664		239,705	0,4662
17		Asphere	-684,567176	-20,000	'CAF2-UV'	198,953	0,2882
18		Sphere	-239,955213	-96,343		192,210	0,5006
19		Sphere	-371,093936	-58,422	'CAF2-UV'	208,205	0,3791
20		Sphere	415,903457	-124,617		205,342	0,4819
21	IMI	Sphere	plane	-30,000		145,352	0,2388
22	M1	Sphere	plane	94,881		164,082	
23		Sphere	783,443511	26,616	'CAF2-UV'	170,678	0,3325
24		Asphere	-347,765826	10,393		172,648	0,436
25		Sphere	-221,571351	15,014	'CAF2-UV'	172,625	0,4792
26		Sphere	-1425,98435	130,243		181,431	0,274
27		Sphere	5167,07679	30,217	'CAF2-UV'	236,667	0,2526
28		Asphere	-411,600995	148,624		239,580	0,2268
29	M2	Sphere	plane	-150,000		339,402	
30		Asphere	-853,73738	-20,000	'CAF2-UV'	273,021	0,329
31		Sphere	-232,398371	-21,824		270,535	0,8916
32		Sphere	-368,19444	-67,745	'CAF2-UV'	275,537	0,7516

33		Sphere	356,248274	-30,922		278,389	0,4622
34		Asphere	-174,204913	-20,000	'CAF2-UV'	264,703	0,7171
35		Sphere	-142,307807	-102,079		242,318	0,9452
36	AS	Sphere	plane	-7,641		257,938	0,3744
37		Sphere	-320,846554	-58,378	'CAF2-UV'	290,282	0,7556
38		Sphere	823,489484	-0,101		290,865	0,3284
39		Asphere	-218,973488	-20,000	'CAF2-UV'	283,679	0,5885
40		Sphere	-170,33788	-27,868		263,871	0,8896
41		Sphere	-247,276664	-90,108	'CAF2-UV'	265,268	0,6962
42		Sphere	343,919771	-1,000		259,153	0,7834
43		Sphere	-124,897304	-36,199	'CAF2-UV'	189,540	0,4119
44		Asphere	-250,343509	-0,908		176,889	0,5175
45		Sphere	-170,592025	-25,037	'CAF2-UV'	165,589	0,4332
46		Asphere	-1480,02994	-7,363		155,817	0,8985
47		Sphere	-705,427094	-23,794	'CAF2-UV'	125,398	0,8941
48		Asphere	-2693,19874	-0,895		92,169	0,9479
49		Sphere	plane	-15,772	'CAF2-UV'	89,164	0,9498
50		Sphere	plane	-6,000		65,738	0,9498
51	W	Sphere	plane	0,000		32,802	0,2375

Table 2

No.	K	C1	C2	C3
7	-1,733588E-09	-3,039865E-13	1,211113E-18	9,121415E-23
9	-7,816544E-09	5,210454E-14	-1,317481E-19	5,653857E-23
15	-7,816544E-09	5,210454E-14	-1,317481E-19	5,653857E-23
17	-1,733588E-09	-3,039865E-13	1,211113E-18	9,121415E-23
24	4,302799E-09	-1,622657E-13	-7,472733E-18	9,256686E-23
28	3,408121E-10	1,843989E-13	3,766164E-19	1,247457E-23
30	4,356029E-09	-1,159648E-13	-1,731928E-18	-1,171287E-23
34	5,997991E-09	1,231574E-13	7,210585E-19	-1,720758E-22
39	5,465935E-09	1,368761E-13	-5,490504E-18	3,341221E-22
44	-3,633610E-09	-1,902535E-12	9,133176E-17	1,106485E-20
46	-2,644679E-10	-1,363066E-12	-2,982278E-16	2,626903E-20
48	1,634110E-10	2,024153E-12	-2,312656E-17	-7,118031E-19

No.	C4	C5
7	6,074314E-28	-1,105790E-31
9	-4,331886E-27	2,130194E-31
15	-4,331886E-27	2,130194E-31
17	6,074314E-28	-1,105790E-31
24	-2,385475E-26	1,224351E-30
28	6,677193E-28	2,084448E-32
30	-3,008881E-27	8,251378E-32
34	6,262844E-27	-4,965774E-31
39	-1,704355E-26	1,485727E-31
44	1,195742E-24	-5,413482E-29
46	-3,513397E-25	-3,816789E-29
48	2,284053E-22	-3,204420E-26

Patent Claims

1. A projection objective for projecting a pattern of a mask arranged in an object plane of the projection objective into an image plane of the projection objective, having:
a pupil surface near the image plane;
a radiance transformation group that is arranged at a distance upstream of the image plane; and
an aperture-generating group arranged downstream of the radiance transformation group;
wherein the radiance transformation group is designed to transform an input radiance distribution with a uniform angular radiance that is substantially independent of beam height into an output radiance distribution with a nonuniform angular radiance that is dependent on beam height, wherein the angular radiance decreases with increasing beam height, at least in a region near a maximum beam height, and
the output radiance distribution is adapted to beam guidance properties of the aperture-generating group in such a way that the sine condition is substantially fulfilled in the image plane for all beams of the input light distribution.

2. The projection objective as claimed in claim 1, wherein the radiance transformation group is arranged in the region of the pupil surface.

3. The projection objective as claimed in claim 1, wherein the radiance transformation group comprises a spherically overcorrecting first optical group and a downstream spherically undercorrecting second optical group.

4. The projection objective as claimed in claim 3, wherein the first optical group is arranged upstream of the pupil surface, and the second optical group is arranged downstream of the pupil surface.

5. The projection objective as claimed in claim 1, wherein the radiance transformation group has a concave lens with a concave face directed toward the image plane.

6. The projection objective as claimed in claim 5, wherein the concave lens is arranged upstream of the pupil surface, and the concave face is directed toward the pupil surface.

7. The projection objective as claimed in claim 5, wherein the concave lens is arranged relative to the pupil surface in such a way that the condition $0 < d/DP < 2$ is fulfilled for a ratio d/DP between a surface distance d of a concave face from the pupil surface and an optically free diameter DP in the pupil surface.

8. The projection objective as claimed in claim 5, wherein the concave face defines a radius of curvature R, and a surface distance d of the concave face from the pupil surface is in the range $0.5 * R < d < 1.5*R$.

9. The projection objective as claimed in claim 5, wherein the concave face is curved and arranged in such a way that maximum sines of the angle of incidence of the penetrating radiation that occur at the concave face are greater than approximately 80%, in particular greater than approximately 90%, of the image-side numerical aperture NA of the projection objective.

10. The projection objective as claimed in claim 5, wherein the concave lens is a meniscus lens.

11. The projection objective as claimed in claim 5, wherein the concave lens has negative refractive power.

12. The projection objective as claimed in claim 3, wherein the spherically undercorrecting second optical group comprises at least one positive lens.

13. The projection objective as claimed in claim 3, wherein the spherically undercorrecting second optical group comprises precisely one biconvex positive lens.

14. The projection objective as claimed in claim 12, wherein the positive lens has an entrance face that is more strongly curved than an exit face of the positive lens.

15. The projection objective as claimed in claim 1, wherein the radiance transformation group comprises a spherically overcorrecting first optical group and a downstream spherically undercorrecting second optical group;
the first optical group being arranged upstream of the pupil surface, and the second optical group being arranged downstream of the pupil surface;
the first optical group having a concave lens with a concave face directed toward the pupil surface; and
the second optical group having precisely one biconvex positive lens.

16. The projection objective as claimed in claim 1, that is a catadioptric projection objective,
which has a catadioptric first objective part that is arranged between the object plane and the image plane and has a concave mirror and a beam deflecting device; and
a second objective part, which is arranged between the first objective part and the object plane,
wherein the radiance transformation group is arranged at a distance upstream of the image plane in the second objective part.

17. The projection objective as claimed in claim 16, wherein the projection objective has precisely one real intermediate image.

18. The projection objective as claimed in claim 16, wherein the beam deflecting device has a fully reflecting first folding mirror with a flat reflecting surface that defines a first reflecting plane that is inclined relative to an object plane segment of the optical axis perpendicular to the object plane and intersects the object plane segment at a mirror distance c from the object plane;
an object field of the projection objective is arranged eccentrically relative to the object plane segment in such a way that an object field distance b exists between the object plane segment and the object field;
and the condition:

$$1.1 \leq P1 \leq 1.9$$

is observed, where $P1 = \frac{c}{b} \cdot \tan(\arcsin(NA \cdot |\beta|))$, NA is the image-side numerical aperture, and β is the magnification ratio of the projection objective.

19. The projection objective as claimed in claim 18, wherein the parameter P1 assumes values between 1.2 and 1.8, in particular between 1.4 and 1.6.

20. The projection objective as claimed in claim 16, wherein a diagonal ratio a between the length of the diagonal of a minimum circle (superfield diagonal) centered on the optical axis and enclosing the object field and the length of a diagonal of the object field is smaller than 1.5 times the image-side numerical aperture NA of the projection objective.

21. The projection objective as claimed in claim 16, wherein no lens or lens group with a refractive power $D = 1/|f| > 1m^{-1}$ is provided in an installation space

between the object plane and the first folding mirror, f being the focal length of the lens or lens group.

22. The projection objective as claimed in claim 16, wherein no lens is arranged in an installation space between the object plane and the first folding mirror.

23. The projection objective as claimed in claim 16, wherein the first folding mirror is arranged in the beam path between the concave mirror and the image plane.

24. The projection objective as claimed in claim 16, wherein a second folding mirror is provided for deflecting the radiation coming from the first folding mirror in the direction of the image plane.

25. The projection objective as claimed in claim 24, wherein the second folding mirror is arranged such that an image plane segment of the optical axis defined between the second folding mirror and image plane runs parallel to the object plane segment of the optical axis.

26. The projection objective as claimed in claim 24, wherein at least one lens or lens group is arranged between the first folding mirror and the second folding mirror.

27. The projection objective as claimed in claim 24, wherein positive refractive power is arranged between the first and second folding mirrors.

28. The projection objective as claimed in claim 16, wherein a total lens mass m_{HOA} of lenses between the first and the second folding mirror is less than 15% of the total lens mass m_{GES} of the projection objective.

29. The projection objective as claimed in claim 16, wherein the first folding mirror is inclined with reference to the object plane segment of the optical axis such that an angle of mirror inclination of more than 45° is enclosed between the reflecting plane and the object plane segment.

30. The projection objective as claimed in claim 29, wherein the angle of mirror inclination is between 47° and 55°.

31. The projection objective as claimed in claim 17, wherein an objective segment arranged between the object plane and intermediate image has a magnification ratio β_{IMI} for which it holds that $0.95 \leq |\beta_{IMI}| \leq 1.2$.

32. The projection objective as claimed in claim 31, wherein $|\beta_{IMI}|$ is between 0.98 and 1.1.

33. The projection objective as claimed in claim 17, wherein the intermediate image is situated in the vicinity of the first folding mirror.

34. The projection objective as claimed in claim 17, wherein the intermediate image is arranged in the optical path between the concave mirror and the first folding mirror.

35. The projection objective as claimed in claim 17, wherein the numerical aperture NA_{IMI} at the intermediate image is substantially equal to the object-side numerical aperture NA_O at the object plane.

36. The projection objective as claimed in claim 17, wherein the numerical aperture NA_{IMI} at the intermediate image is not greater than the numerical aperture NA_O in the object plane.

37. The projection objective as claimed in claim 16, wherein a system aperture is arranged in the catadioptric objective part.

38. The projection objective as claimed in claim 16, wherein a system aperture has an aperture edge that determines the aperture diameter and whose axial position can be varied with reference to the optical axis of the projection objective as a function of the aperture diameter.

39. The projection objective as claimed in claim 1, wherein the image-side numerical aperture is at NA > 0.75 and/or NA > 0.8 and/or at NA > 0.9.

40. The projection objective as claimed in claim 1, wherein all the lenses consist of the same material, in particular of calcium fluoride.

41. The projection objective as claimed in claim 16, that is designed for operating with an F_2 excimer laser whose bandwidth (FWHM) is ≤ 1.5 pm.

42. The projection objective as claimed in claim 1, wherein a number of aspheres are provided, a maximum aspheric sagitta being greater than 300 μm preferably for at most half of the aspheres.

43. The projection objective as claimed in claim 1, that has fewer than 20 refractive components comprising refractive power.

44. The projection objective as claimed in claim 16, wherein at least two lenses with negative refractive power are arranged in the vicinity of the concave mirror.

45. The projection objective as claimed in claim 16, wherein the concave mirror has a diameter that is more

than 20% of a distance between the object plane and concave mirror.

46. The projection objective as claimed in claim 16, wherein more lenses with negative refractive power than with positive refractive power are arranged in a doubly traversed region between object plane and concave mirror.

47. The projection objective as claimed in claim 1 that is designed for ultraviolet light from a wavelength region between approximately 120 nm and approximately 260 nm, in particular for an operating wavelength of approximately 157 nm.

48. A projection exposure machine for microlithography, having an illuminating system and a projection objective, wherein the projection objective is designed in accordance with one of the preceding claims.

49. A method for fabricating semiconductor components and other finely patterned components, having the following steps:
providing a mask with a prescribed pattern;
illuminating the mask with ultraviolet light of a prescribed wavelength; and
projecting an image of the pattern onto a photosensitive substrate, arranged in the region of the image plane of a projection objective, with the aid of a projection objective in accordance with one of claims 1 to 47.

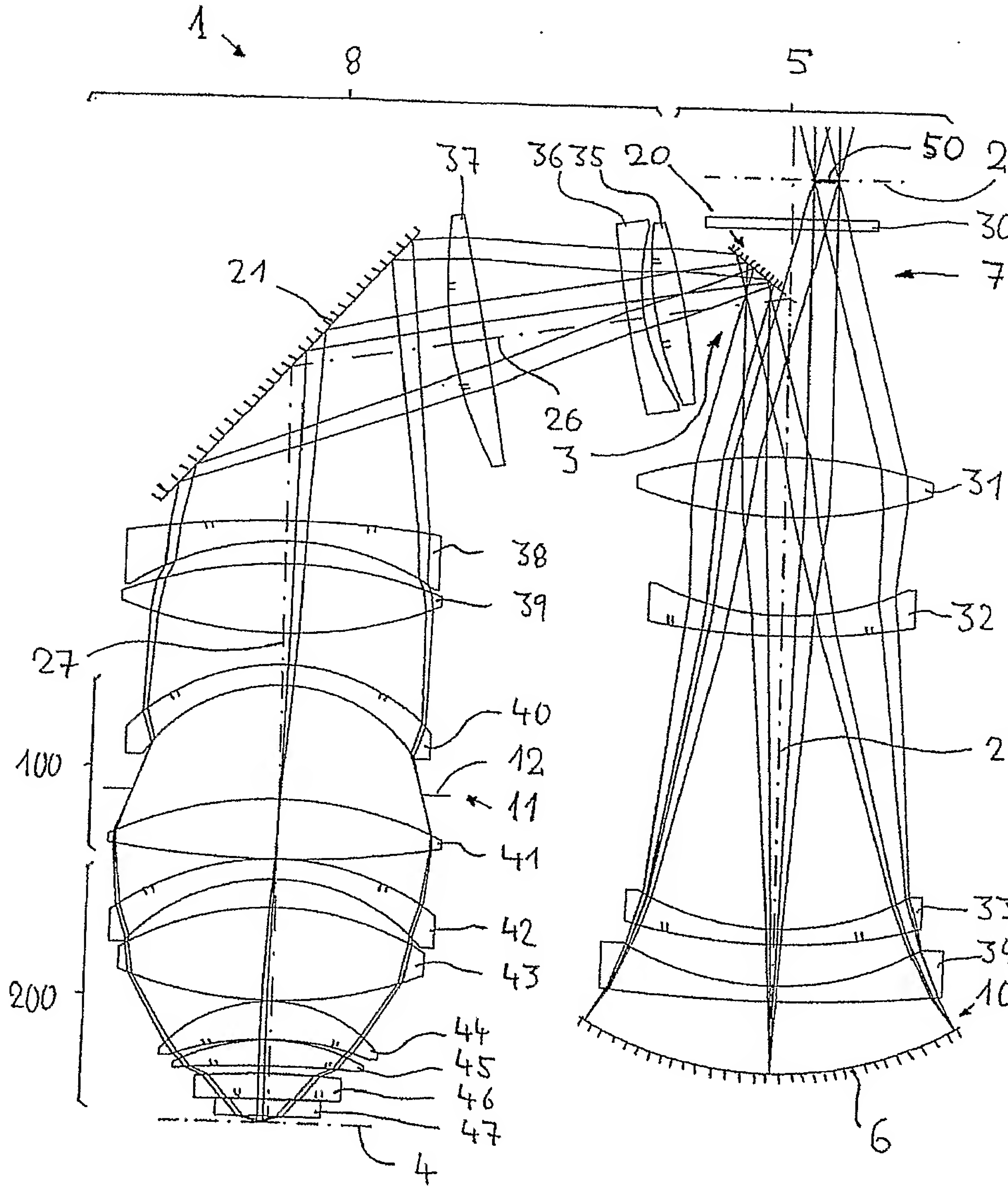
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Fig. 1

Fig. 2

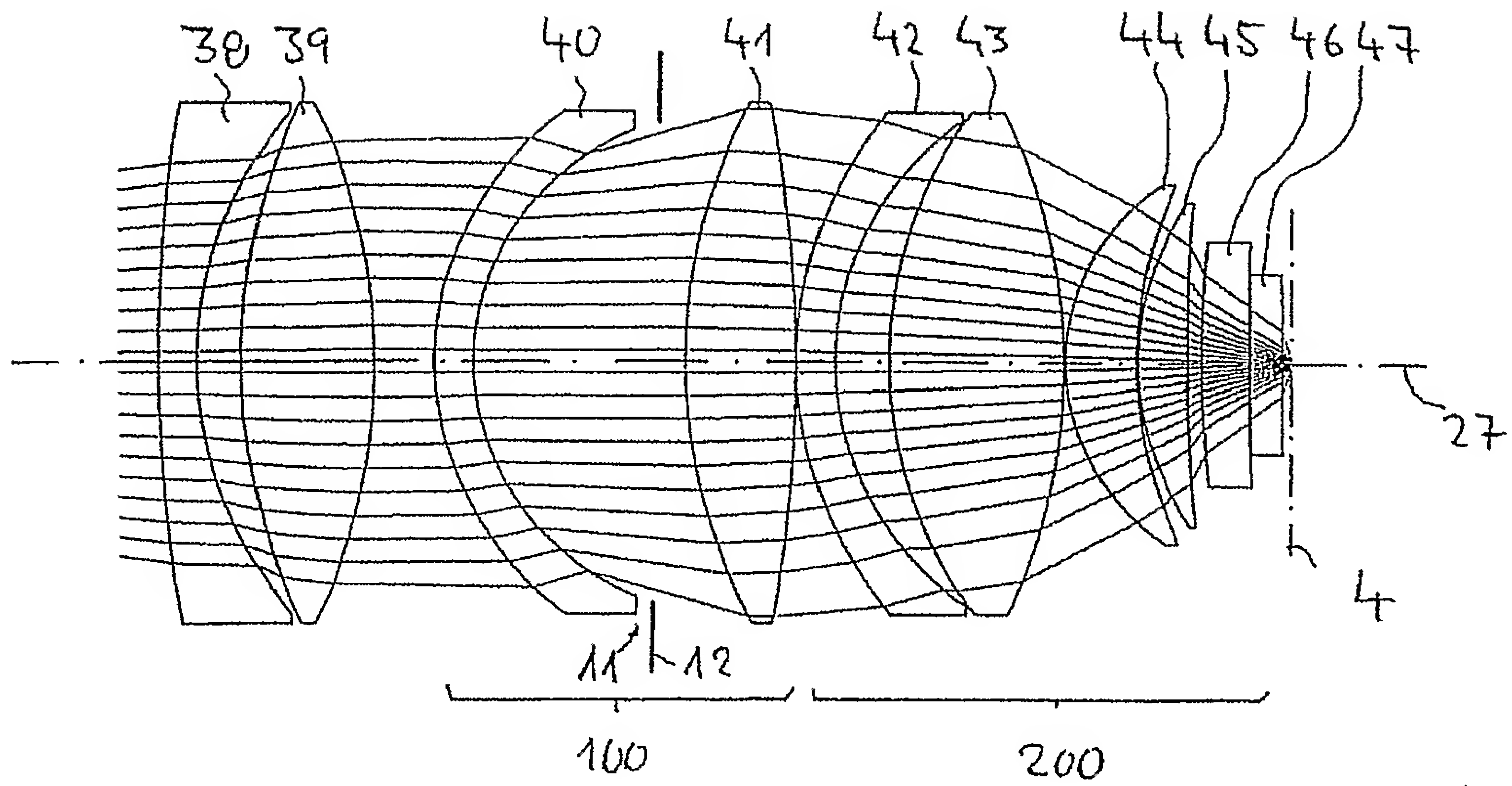
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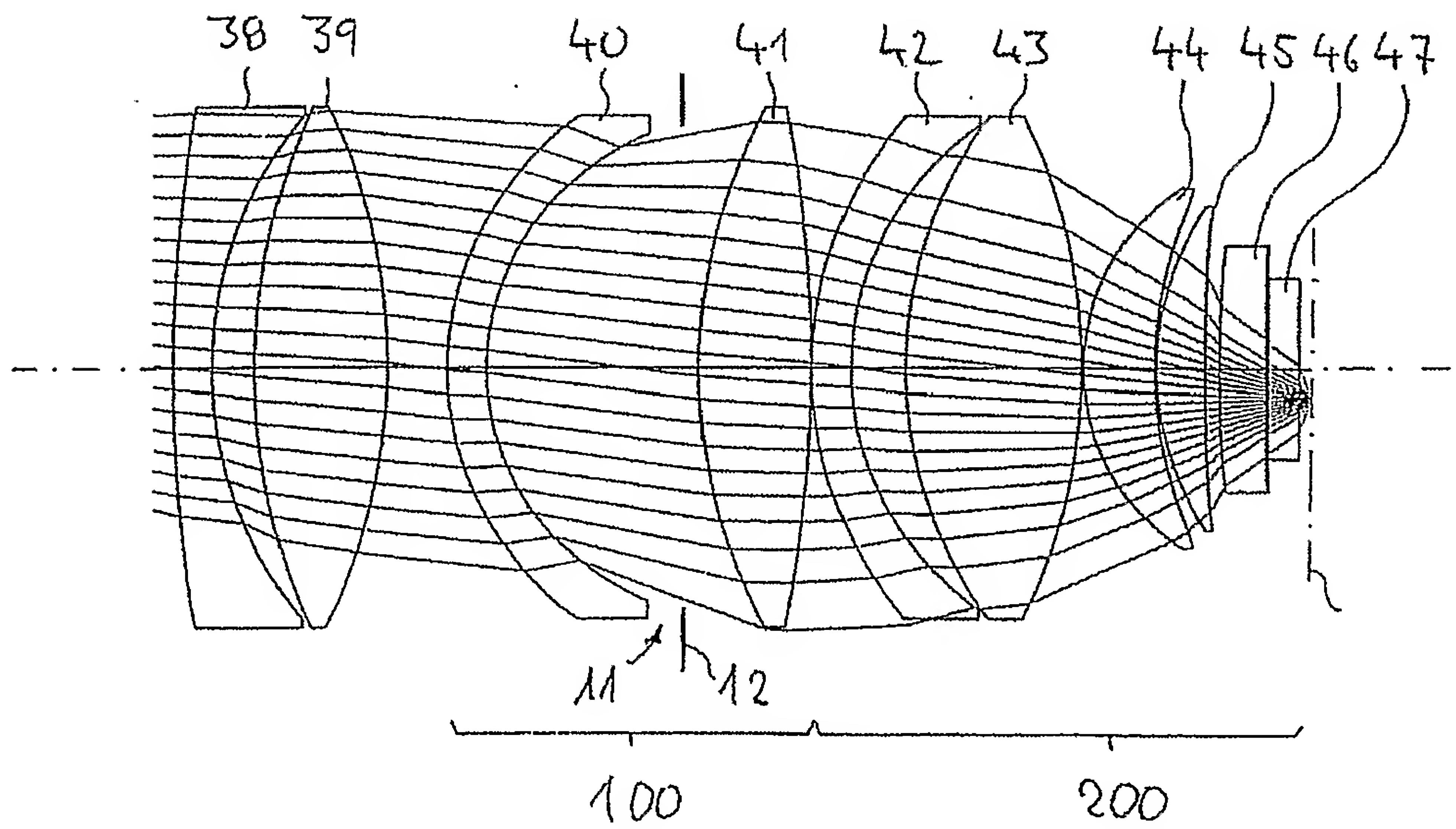
Fig. 3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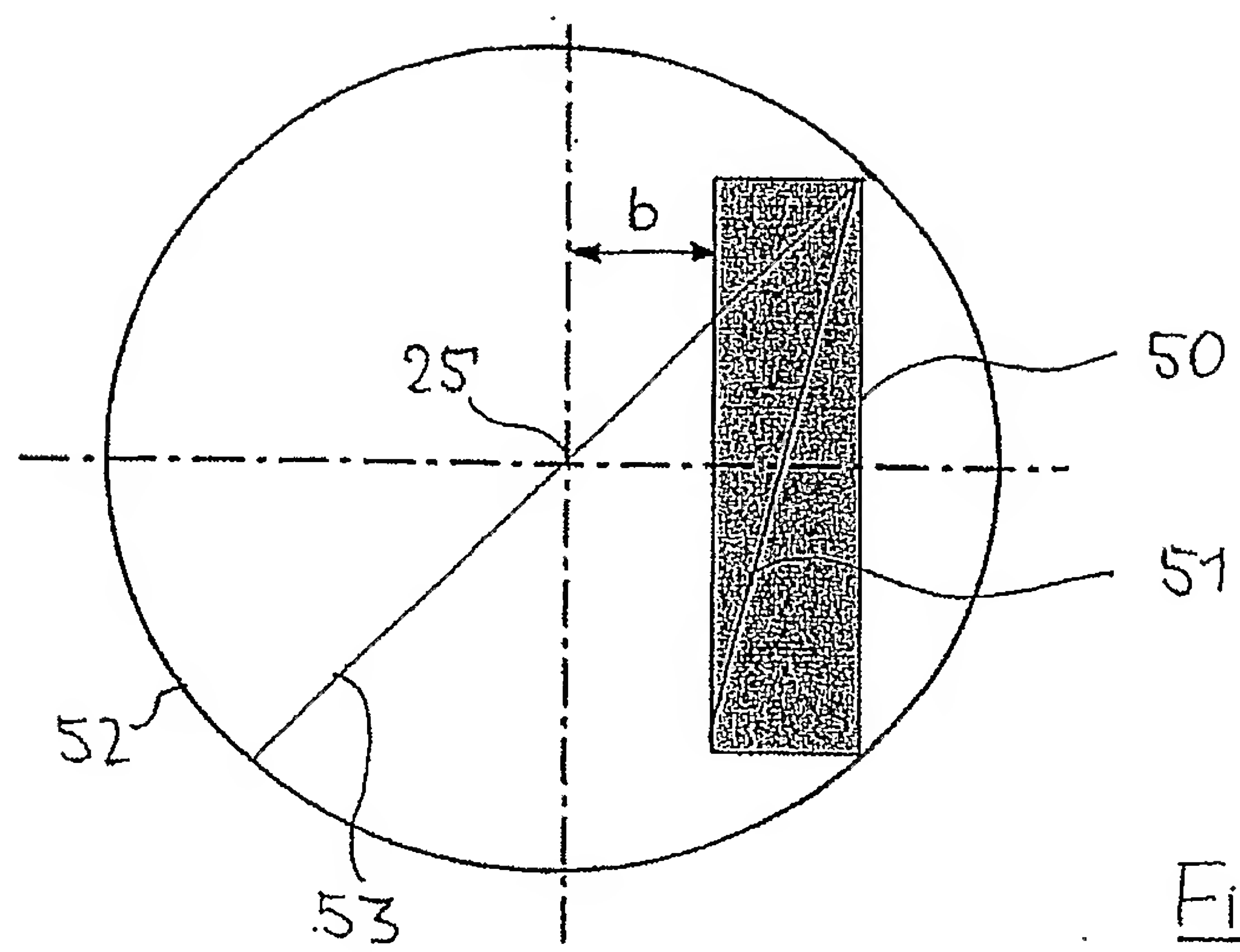

Fig. 4

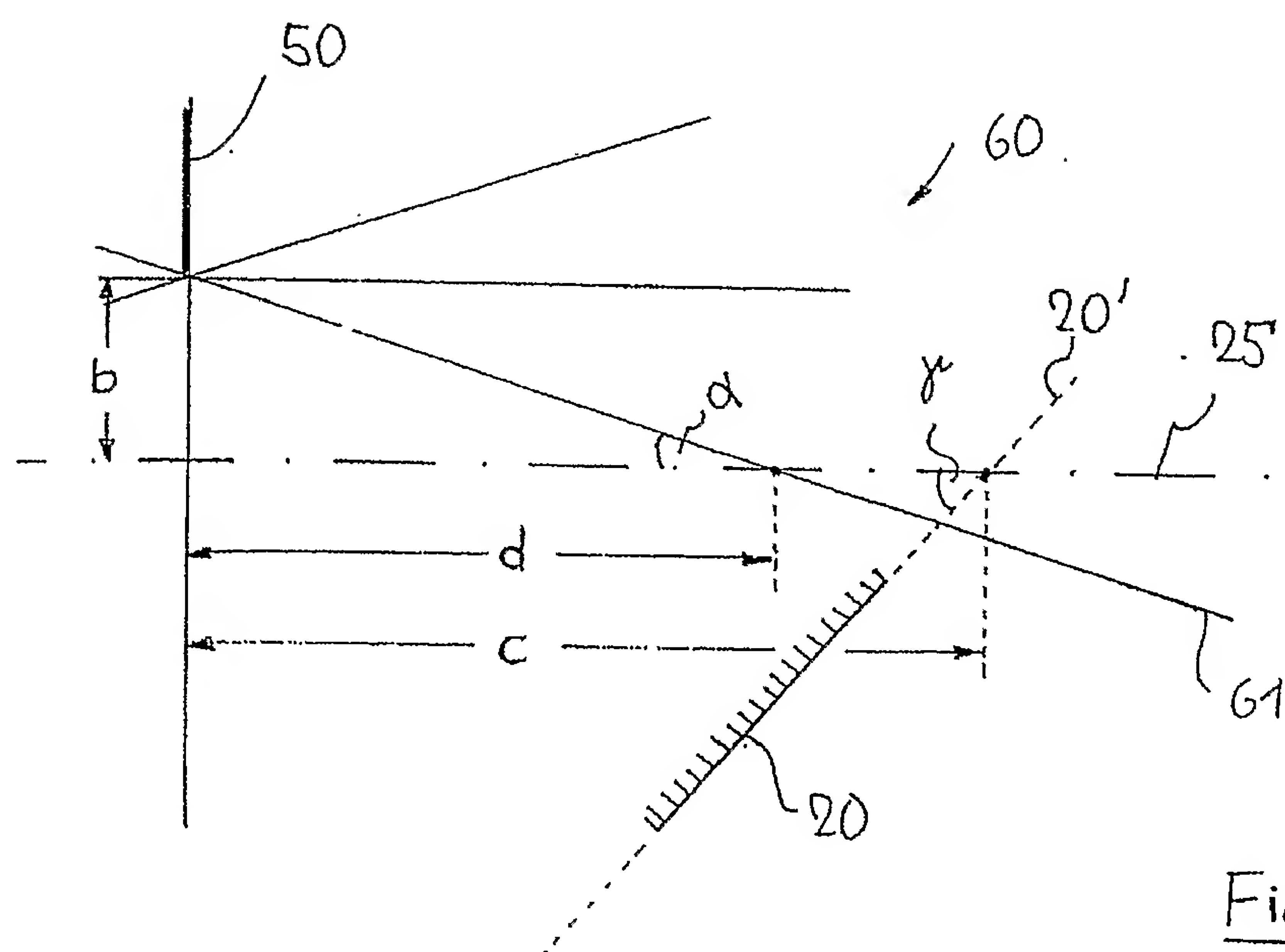

Fig. 5